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MICROWAVE FIBER OPTICS DELAY LINE

C. Slayman and H.W. Yen

Hughes Research Laboratories

3011 Malibu Canyon Road

Malibu, CA 90265

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A microwave delay line is one of the devices used in EW systems for preserving the frequency and phase contents of rf signals. For such applications, delay lines are required to have large dynamic range, wide bandwidth, low insertion loss, and a linear response. The basic components of a fiber-optics delay line are: an optical source, a wideband optical modulator, a spool of single-mode fiber with appropriate length

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to provide a given microwave signal delay, and a high-speed photodetector with an rf amplifier. This contract program is to study the feasibility of such a fiber-optic delay line in the frequency range of 4.0 to 6.5 GHz. The modulation scheme studied is the direct modulation of injection lasers. The most important issue identified is the frequency response of the injection laser and the photodetector.

We found that, because of the large mismatch between the laser and the microwave driver, it is not possible to have an efficient matching network over the entire band of interest (4.0 to 6.5 GHz). We also observed a significant dip in the laser modulation response at frequencies below the resonance frequency. This roll-off in the frequency response can be as large as 15 to 20 dB over the 2.5-GHz band. Although an equalization network could be used to smooth out the response, the excess insertion loss would be unacceptable. The conclusion of our study is that the direct-modulation approach in the 4.0- to 6.5-GHz band cannot produce a system that meets the specifications. However, the possibility of using an external modulator should not be ruled out. Wideband traveling-wave modulators have been demonstrated with bandwidths in excess of 10 GHz. Our initial calculations indicated that spurious-free response in excess of 30 dB dynamic range can be obtained with such modulators.

PREFACE

The following personnel contributed to the research work reported here: C. Slayman, H.W. Yen, L. Figueroa, K. Walsh, A. Horvath, and D.F. Lewis.

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SECTION 1

INTRODUCTION AND SUMMARY

A microwave delay line is one of the devices used in EW systems for preserving the frequency and phase contents of rf signals. For such applications, delay lines are required to have large dynamic range, wide bandwidth, low insertion loss, and a linear spurious-free response. Delay-line performance specifications are listed in Table 1. The bulk acoustic-wave delay lines used in current systems have several limitations. Fiber-optic delay lines appear to provide a viable alternative to meeting the systems needs and to offer promise of substantial improvements in the future. As shown in Table 1, the delay times required are 1.75 μsec and 3.85 μsec. Since the speed of light in fibers is about 2×10^8 m/sec, these delay times correspond to fiber lengths of 350 and 770 m, respectively. Low-loss single-mode fibers up to 1 km in length can be fabricated readily and packaged compactly on small-diameter spools. As a rough estimate, the excess loss of optical signals due to laser-to-fiber and fiber-to-detector coupling is about 10 dB.

Table 1. Microwave Delay-Line Performance Specifications

Microwave signal delays: 1.75 μsec and 3.85 μsec
Transmitter and receiver combined bandwidths: 2.5 GHz
Delayed signal amplitude variation over the bandwidth of 2.5 GHz: ±1 dB
Frequency range: 4.0 to 6.5 GHz
Delay-line dynamic range: ≥30 dB
Delay-line insertion loss: ≤40 dB
Triple transit echo level: 40 dB below desired signal
AM-to-PM distortion: 1°/dB

The basic components of a fiber-optics delay line are an optical source, a wideband optical modulator, a spool of single-mode fiber with appropriate length to provide a given microwave signal delay time, and a high-speed photodetector with an rf amplifier. The purpose of this contract program was to study the feasibility of such a fiber-optic delay line in the frequency range of 4.0 to 6.5 GHz. The modulation scheme studied was the direct modulation of injection lasers. The most important issue identified is the frequency response of the injection laser and the photodetector. Direct modulation is the simplest way of modulating an injection laser. The frequency response of the laser depends on the dc bias level. The small-signal frequency response of injection lasers has a resonance-like peak. The modulation index as a function of frequency stays relatively constant below the resonance frequency and increases rapidly to its peak value at the resonance frequency. Beyond the resonance frequency, the modulation response drops sharply. Therefore, for all practical purposes the resonance frequency represents the highest frequency at which the lasers can be modulated efficiently. We have studied several lasers and characterized them in terms of input reflection coefficient (or input impedance) as well as small-signal frequency response. We observed the anticipated modulation resonance and its dependence on the dc bias level. However, we did not have a scanning Fabry-Perot available to perform independent measurements of the modulation index. Instead, we resorted to using a high-speed photodetector (rise time <50 psec) to detect the modulated laser output. The same detector was also used to study the transmission characteristics of the link. We found that, because of the large mismatch between the laser and the microwave driver, it was not possible to design an efficient matching network over the entire band of interest (4.0 to 6.5 GHz). We also observed a significant dip in the laser modulation response at frequencies below the resonance frequency. This roll-off in the frequency response could be as large as 15 to 20 dB over the 4.0- to 6.5-GHz range. We believe that this sharp drop below the resonance frequency was caused by lateral carrier diffusion. It appeared in almost all diode lasers examined, and the effect was more

pronounced for CSP lasers than for BH lasers. The roll-off is one of the difficulties encountered in this study. Although an equalization network might be used to smooth out the response, the excess insertion loss would be unacceptable. The conclusion of our study is that the direct-modulation approach in the 4.0- to 6.5-GHz range cannot produce a system that meets the specifications listed above. However, the possibility of using an external modulator should not be ruled out. Wideband traveling-wave modulators have been demonstrated in the laboratory to have bandwidths in excess of 10 GHz. Our initial calculations indicated that such a device when biased at $\pi/2$ point can be used in an analog system that requires 30-dB dynamic range (1 dB compression).

SECTION 2

DIRECT MODULATION OF INJECTION LASERS

Semiconductor lasers with their small size, light weight, and ease of operation have become the most desirable optical sources in various high-data-rate communication systems. Since their invention, semiconductor lasers have been improved steadily, and long-life cw lasers now are available commercially. Single transverse and longitudinal mode operation is possible by properly controlling device structure and operating conditions. A good laser should have a low bias current for a given output power level, a sharp knee in its light-versus-current characteristics at threshold, and a linear relationship between the output power and the driving current above threshold.

In this study, we used lasers from Hitachi Inc. (models HLP-2400 and HLP-1400). The HLP-2400 laser is of the buried-heterostructure (BH) type with an emitting area on the order of 1 μm by 1 μm. Typical threshold is ∿20 mA, and typical output power is ∿1 mW. The HLP-1400 laser is of the channeled-substrate-planar (CSP) structure, with a threshold of ∿60 mA and an output power of ∿5 mW.

The easiest way to modulate an injection laser output is to modulate the laser current directly. The frequency response of the laser can be analyzed using a pair of simple rate equations:

$$\frac{dn}{dt} = \frac{I}{eV} - Gns - \frac{n}{\tau_s}$$

$$\frac{ds}{dt} = Gns - \frac{s}{\tau_p} \quad ,$$

where n is the electron inversion density, s is the photon density, I is the laser driving current, e is the electronic charge, V is the volume of the laser active region, G is a constant related to the stimulated transition process, τ_s is the spontaneous lifetime of the electrons, and τ_p is the photon lifetime in the laser cavity. Since this set of equations is nonlinear, exact analytical solutions are difficult to obtain. However, approximations can be used to calculate

the small-signal response of the laser. If we define a normalized modulation depth function $f(\omega)$ as the ratio of the modulation response at frequency ω to that at zero frequency, then $f(\omega)$ can be shown to be

$$f(\omega) = \frac{\omega_o^2}{\left|(\omega_o^2 - \omega^2)^2 + \gamma^2\omega^2\right|^{1/2}} ,$$

where

$$\omega_o^2 = \frac{1}{\tau_p\tau_s}\left(\frac{I}{I_{th}} - 1\right) ,$$

$$\gamma = \frac{1}{\tau_s}\frac{I}{I_{th}} ,$$

I_{th} is the threshold current of the laser, and I is the dc bias current.

Figure 1 shows a plot of $f(\omega)$ with I/I_{th} as a parameter. It is clear from the plot that, to increase the bandwidth over which the laser frequency response is flat, the laser must be biased as high above threshold as possible. Unfortunately, this cannot be done arbitrarily since most lasers will not survive a constant driving current of more than 2 to 3 times the threshold at room temperature. Figure 2 plots the measured resonance frequencies of a BH laser as a function of the laser bias level. From the slope of the graph, we determined that the product $\tau_p\tau_s$ is about 4×10^{-20} sec^2. Besides the amplitude response variation under resonance conditions, there is also a phase change of 180° in the detected microwave signal. Since such amplitude and phase variations are not desirable for delay-line applications, the laser resonance must be kept out of the frequency band of interest.

During our initial studies, we chose to use HLP-2400 BH lasers because of their low threshol' currents. A major task in the laser study is to impedance match the laser to the rf driving circuit between 4 and 6.5 GHz for efficient modulation. Three Hitachi lasers were measured using an automatic network analyzer (two BH type and one CSP type).

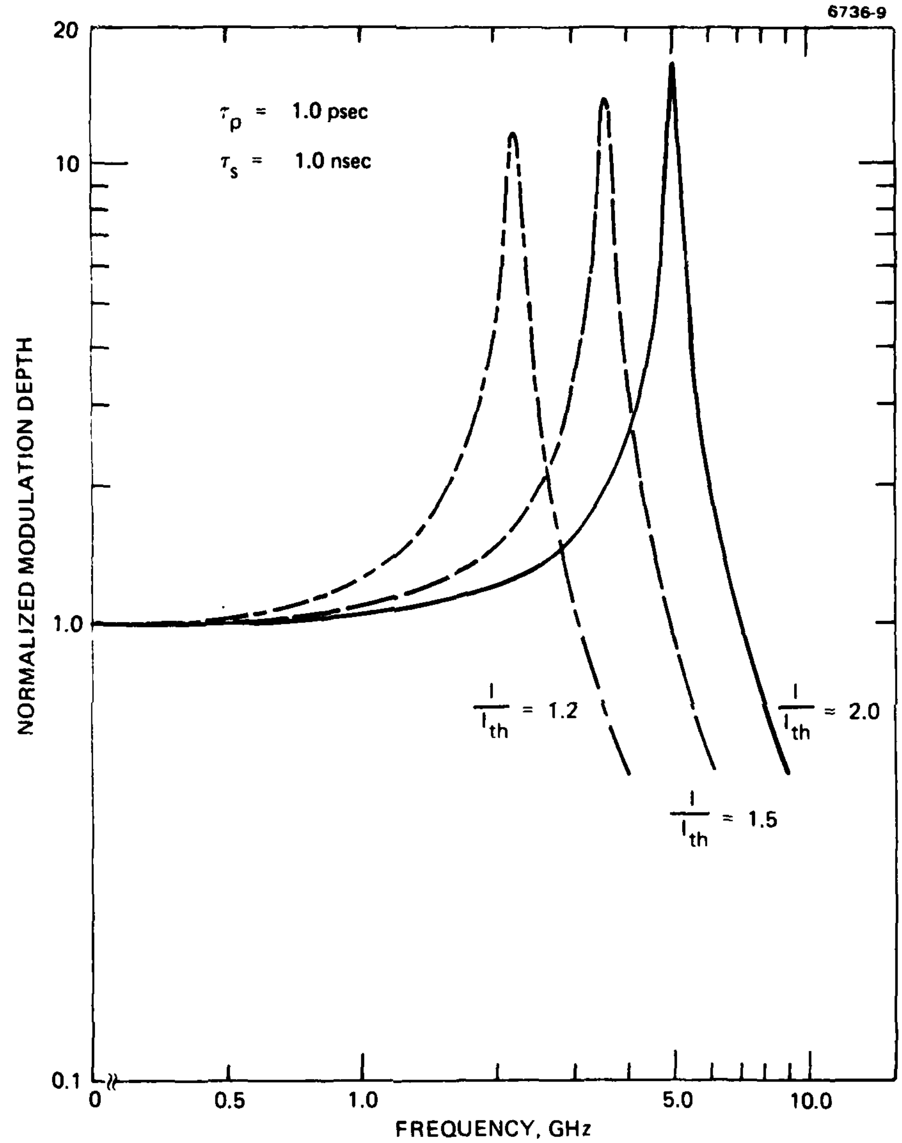

Figure 1. Frequency dependence of the normalized modulation depth of an injection laser.

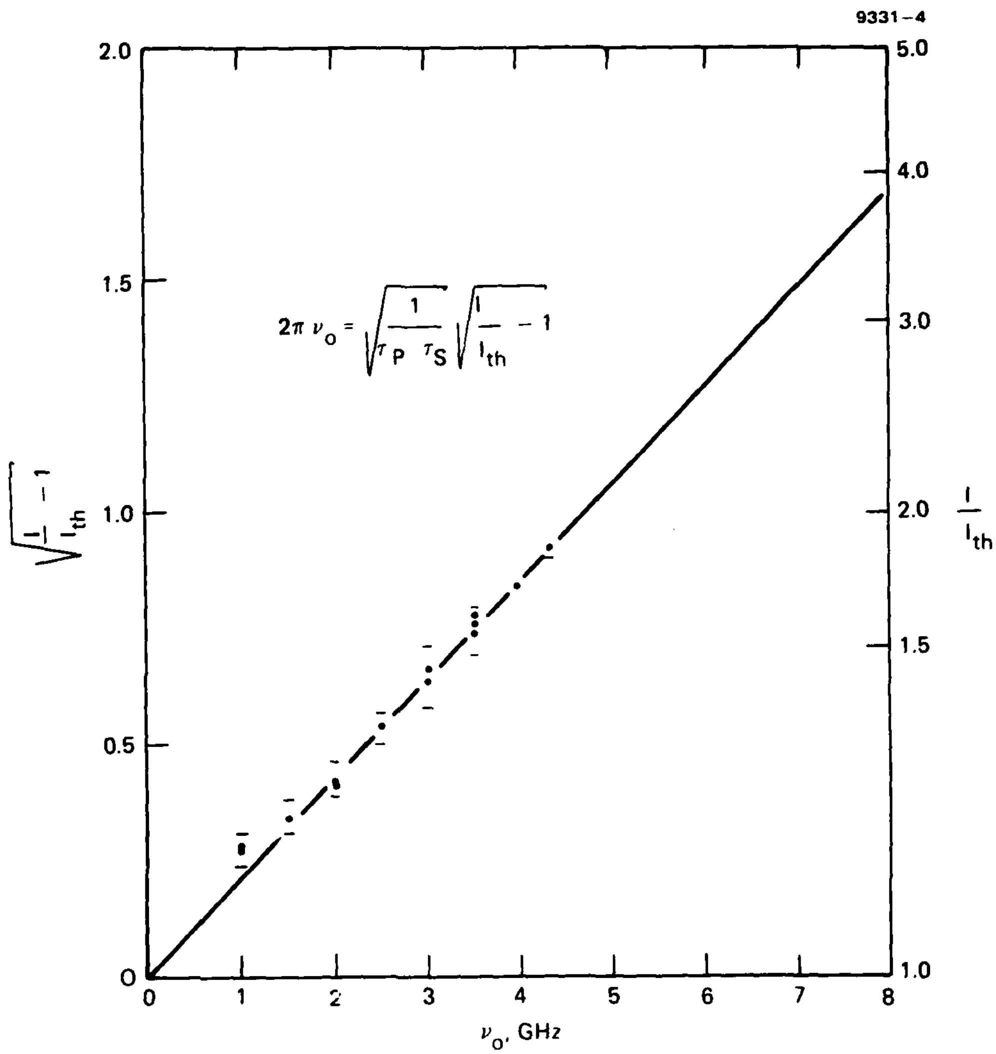

Figure 2. Injection laser small-signal resonance frequency, $\nu_o = \omega_o/2\pi$, versus bias current.

A simple test fixture was designed and manufactured which consisted of a section of microstrip on an alumina substrate, an APC-7 launcher, a shorted reference line, and a copper block heatsink. The lasers were mounted at the end of the stripline opposite the launcher.

Each laser was characterized at several bias levels from 100 MHz to 10 GHz in 100-MHz steps. Of course, for this program we are mostly interested in the frequency range of 4 to 6.5 GHz. Figure 3 shows the S_{11} plots of one of the lasers (HLP-2400U). Each data point corresponds to a different input frequency. Starting from 100 MHz, the frequency increases clockwise and ends at 10 GHz. Figure 3(a) is for the laser biased below threshold, and Figure 3(b) is for the laser biased above threshold. There is very little difference between these two cases except at low frequencies. Attempts were made to derive an equivalent circuit of the injection lasers based on the measured S_{11} values. The equivalent circuit would be useful in designing a matching network and in understanding the frequency response of the laser. However, it is difficult to generate a circuit with characteristics matching the measured values over the entire bandwidth. We have found that a BH laser diode chip alone can be approximated as a 13-Ω resistor in parallel with a 13-pF capacitor. Based on this parallel RC equivalent circuit, one can calculate the lowest possible constant reflection from the laser when driven by a microwave signal of a given bandwidth. This calculation assumes no parasitic elements outside of the diode chip. From Fano's rule, we have

$$\int_0^\infty \ln \left|\frac{1}{\Gamma}\right| \, d\omega = \frac{\pi}{RC} \quad ,$$

where $|\Gamma|$ is the magnitude of the reflection coefficient. For a constant $|\Gamma|$, the integral becomes

$$\ln \left|\frac{1}{\Gamma}\right| \omega_{bw} = \frac{\pi}{RC} \quad ,$$

and hence

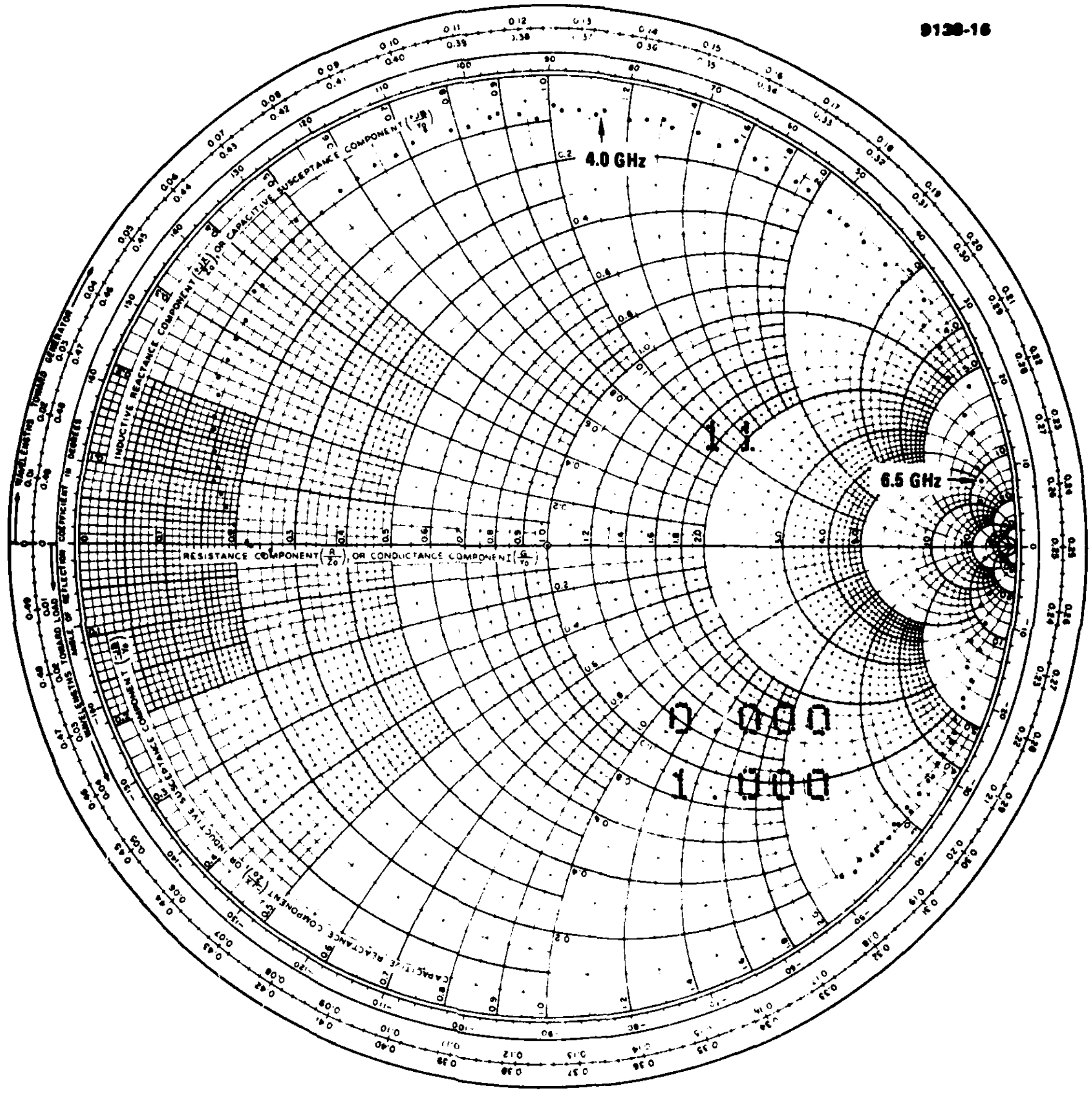

Figure 3(a). S_{11} plot of a BH laser (biased below threshold).

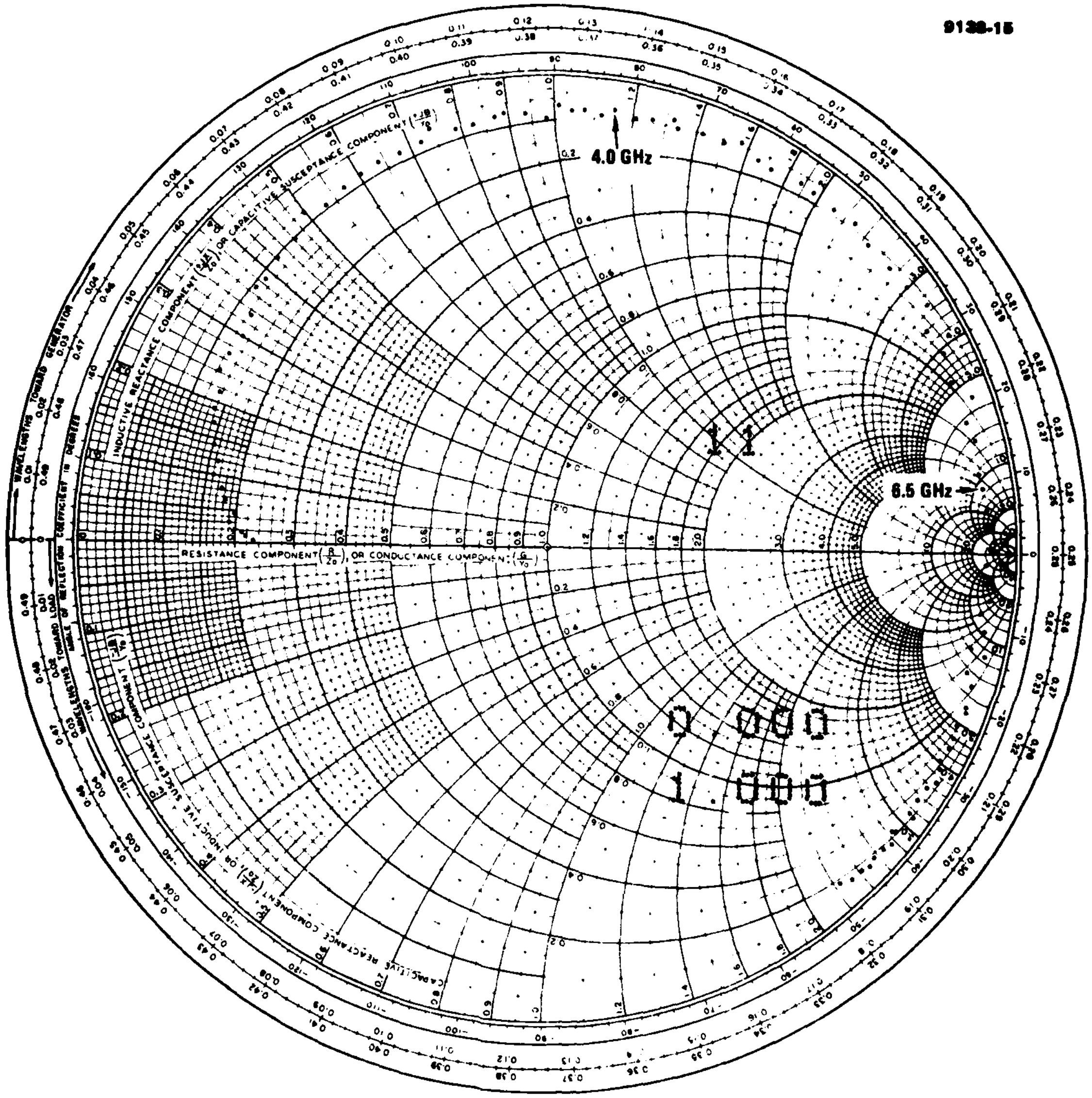

Figure 3(b). S_{11} plot of a BH laser (biased above threshold).

$$|\Gamma| = \exp\left(\frac{-1}{2f_{bw}RC}\right).$$

Substituting the values R = 13 Ω, C = 13 pF, and f_{bw} = 2.5 GHz yields $|\Gamma|$ = 0.306, which represents the best coupling achievable if a laser diode chip with a proper matching network is used. In practice, however, the parasitics from the device package degrades the performance. Tables 2 and 3 summarize the results of two transmission-loss calculations for a BH laser with and without a matching network. It appears that broadband matching networks do not significantly reduce microwave reflection loss. Thus, we decided to carry out our experiments by driving the lasers without a matching network.

Table 2. Transmission Loss of BH Laser without Matching Network

Frequency, GHz	$\|\Gamma\|$	Loss, dB	
4.0	0.912	7.74	8.28 ± 0.54 (dB)
4.5	0.918	8.03	
5.0	0.921	8.19	
5.5	0.925	8.40	
6.0	0.932	8.81	
6.5	0.930	8.69	

Table 3. Transmission Loss of BH Laser with Best Broadband Matching Circuit Computed so Far

Frequency, GHz	$\|\Gamma\|$	Loss, dB	
4.0	0.880	6.47	5.43 ±1.05 (dB)
4.5	0.856	5.73	
5.0	0.824	4.93	
5.5	0.797	4.38	
6.0	0.819	4.64	
6.5	0.842	5.36	

SECTION 3

PHOTODETECTOR CHARACTERIZATIONS

Because of the bandwidth requirement of the delay line, we need a high-speed photodiode to demodulate the microwave signal. In general, for a photodiode with 10 to 90% rise time t_r, the -3 dB cutoff frequency will be given by

$$f_{3dB} = \frac{0.35}{t_r} .$$

Thus, a photodiode with 0.5-nsec rise time will yield a cutoff frequency of 700 MHz; therefore, to get a 7-GHz cutoff frequency would require a detector with a rise time of $\sim$50 psec.

The upper frequency response of a photodiode is governed by two effects: transit time phenomena and circuit RC time considerations. To obtain high-frequency response, all the photo-carriers must be generated in the high field region of the diode so that they travel at the field saturation velocity v_{sat}. Diffusion currents will arise when carriers are generated in low field regions and give rise to a low-frequency cut-off. If w is the width of the depletion region (or intrinsic region in a PIN diode), then the carrier transit time is:

$$\tau = w/v_{sat} .$$

It can be shown that the rf power available from the photodiode is down by 3 dB at the frequency

$$f_\tau \approx 0.45/\tau$$

due to transit time effect alone. Nothing can be done about transit time problems except to use a detector with a narrow intrinsic or depletion region. However, this would increase the detector capacitance and reduce the device quantum efficiency. The RC time constant of the detector can be extended to higher frequencies at the expense of the absolute gain if a small load impedance is used. When the load resistance

becomes comparable to the detector series resistance, a further decrease in load resistance will not increase the bandwidth.

There are only a few high-speed photodetectors that are suitable for the 4.0- to 6.5-GHz range. Three of the possible candidates are: (1) a GaAs/GaAlAs avalanche photodiode from Rockwell ($t_r \simeq 35$ psec), (2) a silicon avalanche photodiode from Spectra Physics ($t_r \lesssim 50$ psec), and (3) a microwave GaAs FET ($t_r \lesssim 50$ psec). Since the Rockwell diode exhibits the best characteristics, we have concentrated our efforts on it. We measured the dc saturation level and the power linearity of the detector as a function of its reverse bias voltage.

The experimental set-up for detector characterization is shown in Figure 4. The output of a Hitachi HLP-2400U laser was collected and focused using an 18x microscope objective lens onto the Rockwell detector. A beam splitter was used to direct part of the beam to a photometer for monitoring. The photodiode was reverse biased through a current-limited bias supply. The bias supply was designed to give a bias voltage of 30 V maximum and current flow of no more than 400 μA. The loaded characteristic curve of the current limiter is shown in Figure 5. A slight voltage drop was present due to the series resistance in the circuit. Figure 6 shows the measured detector current I versus the incident optical power P for detector bias levels of 5 V and 30 V. With 30 V of bias, the detector response is linear up to 1 mW of input optical power with a dynamic range of better than 40 dB. Figure 7 is a similar plot but on a linear to logarithmic scale; it shows more clearly the dependence of detector responsivity on bias voltage. Detector responsivity was measured to be 0.31 μA/μW. For the laser wavelength used (0.814 μm), this gives a device quantum efficiency of 0.47. Figure 8 shows detector current as a function of detector bias voltage with input optical power as the parameter. The curves show that under large bias the detector is linear up to about 1 mW of optical input power, while at low bias the linear dynamic range is reduced by almost 20 dB.

The bandwidth of the Rockwell photodiode could not be determined accurately because a scanning Fabry-Perot was not available. However, from the various experimental observations and the rise time information, we concluded that the detector has a reasonably flat response over the frequency range of interest.

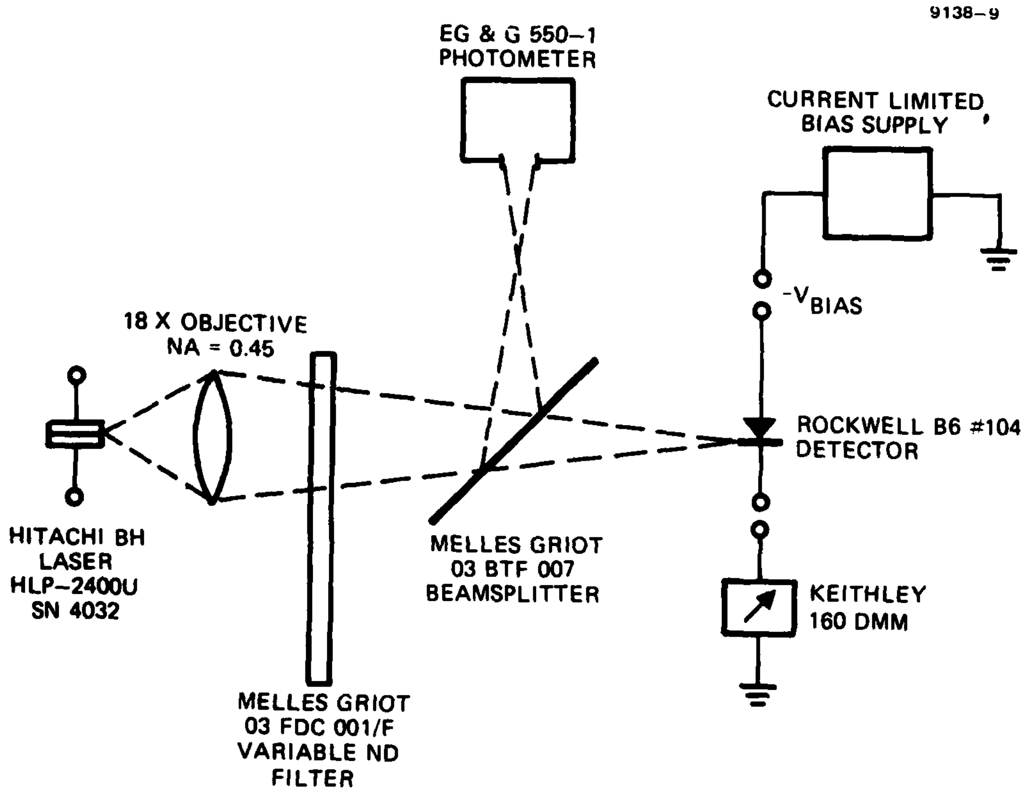

Figure 4. Photodetector response test setup.

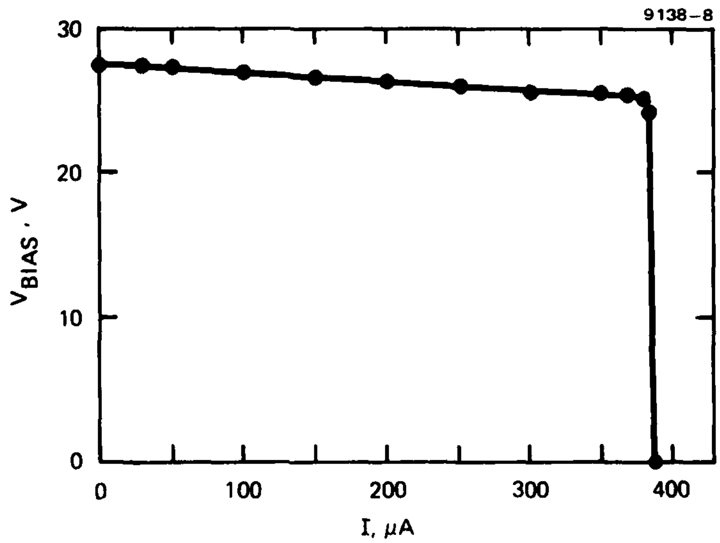

Figure 5. Voltage versus current characteristic of the photodetector power supply.

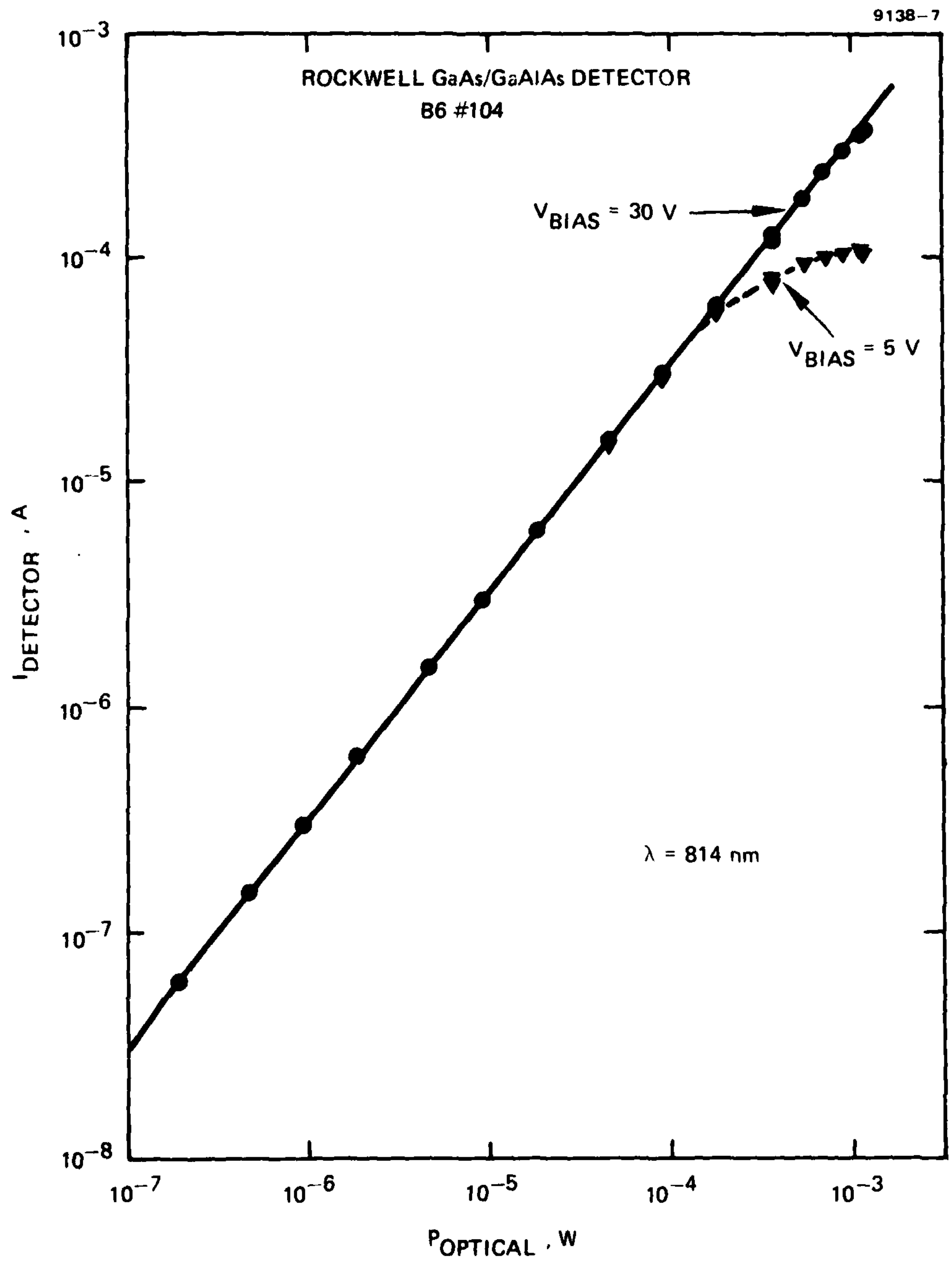

Figure 6. Photodetector current versus optical input power.

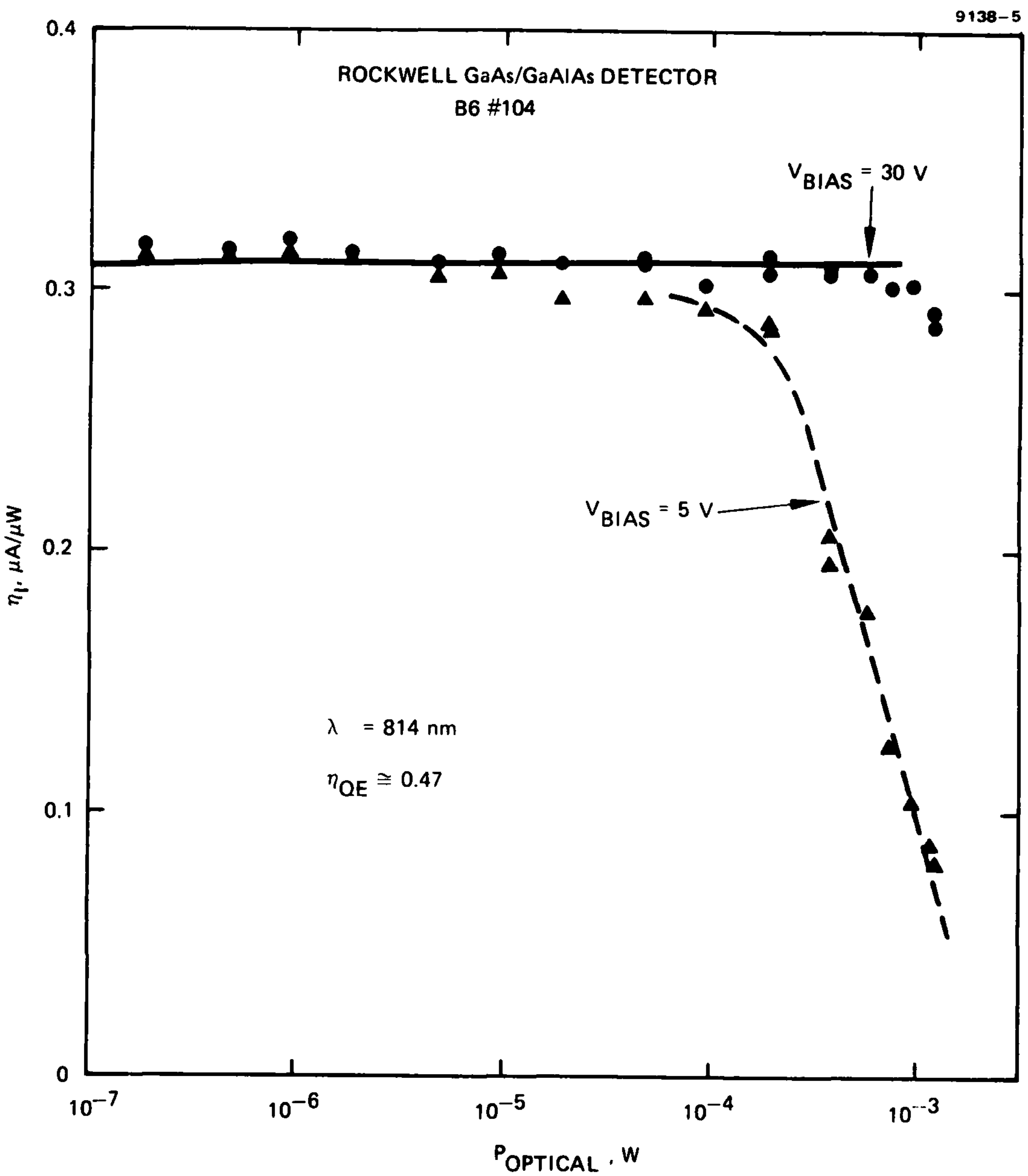

Figure 7. Photodetector responsivity versus optical input power.

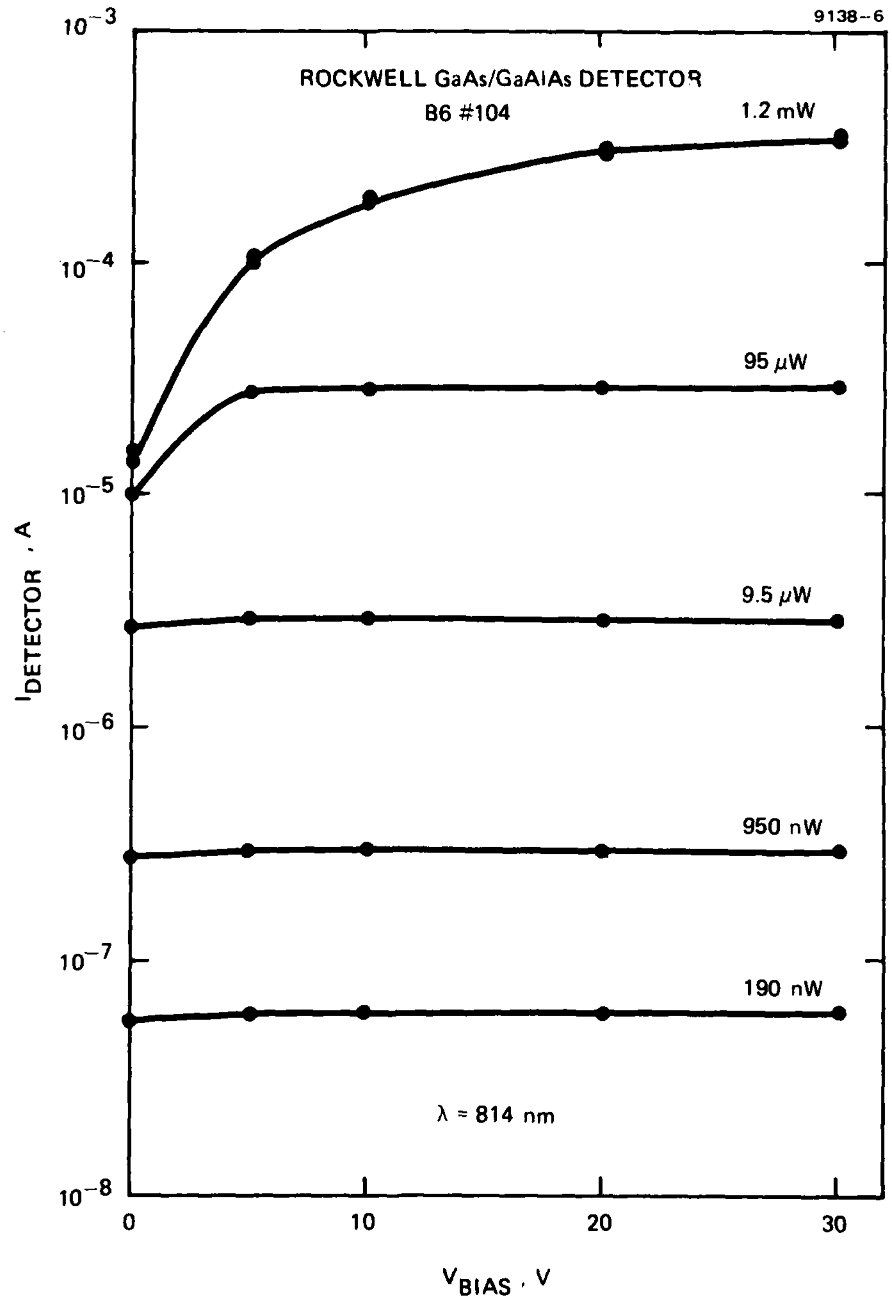

Figure 8. Detector current versus bias voltage at various input optical power levels.

SECTION 4

MEASUREMENTS OF TRANSMISSION CHARACTERISTICS

The microwave transmission properties of the injection laser/high-speed photodetector combined link (without fiber) were characterized. We found that to obtain a reasonably flat frequency response would require biasing the laser up to 3 times above threshold.

The experimental arrangement is shown in Figure 9. The output of an rf generator (sweep oscillator) was fed to an S-parameter test set. The test set has two ports: an output port (port 1) and an input port (port 2). The injection laser was connected to port 1 so that the microwave signal was superimposed on the dc bias of the laser to modulate the optical output. The output of the laser was collected by an 18X objective lens and focused onto a high-speed photodetector through a variable neutral density filter. We have used both an optoelectronics PD 10-2 PIN photodiode and a Rockwell GaAs/GaAlAs heterojunction photodiode. The detected signal was amplified using a low-noise GaAs FET amplifier (∿26 dB gain) before going into port 2 of the S-parameter test set to complete the loop for transmission measurements. We can also feed the amplifier output to an rf spectrum analyzer to determine the microwave signal frequency and power.

Figure 10 shows the transmission characteristics of the laser-detector combination. The transmission parameter (S_{21}) was measured with the laser biased at 42 mA (or $I = 1.85\ I_{th}$). The amplitude of S_{21} represents the insertion loss of the link. As shown in the upper picture of Figure 10, $|S_{21}|$ had a resonance peak at about 4.3 GHz, and beyond that the loss increased at a rate of 12 dB/GHz. The resonance peak was not sharp, which seems to be characteristic of BH lasers. The phase of S_{21} as shown in the lower picture of Figure 10 goes through a 180° change near 4.3 GHz corresponding to the resonance. It is obvious that, to obtain a smooth, flat frequency response, the laser resonance must be kept out of the frequency band of interest.

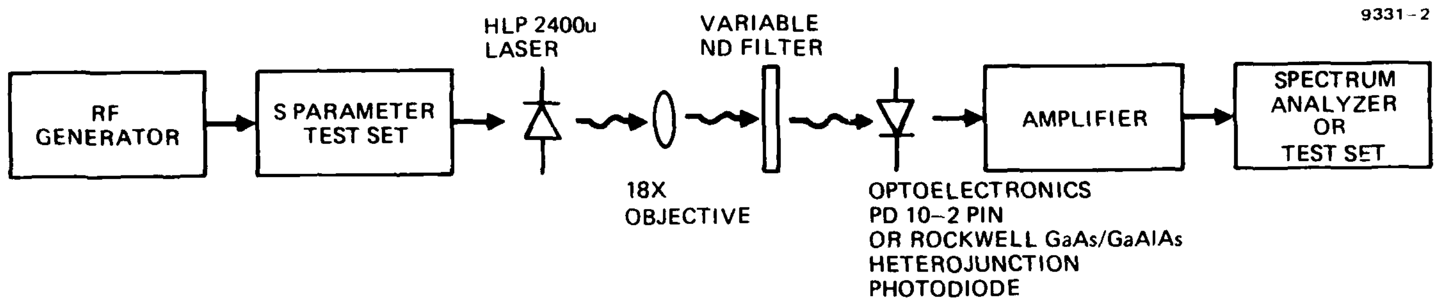

Figure 9. Experimental arrangement to measure transmission characteristics.

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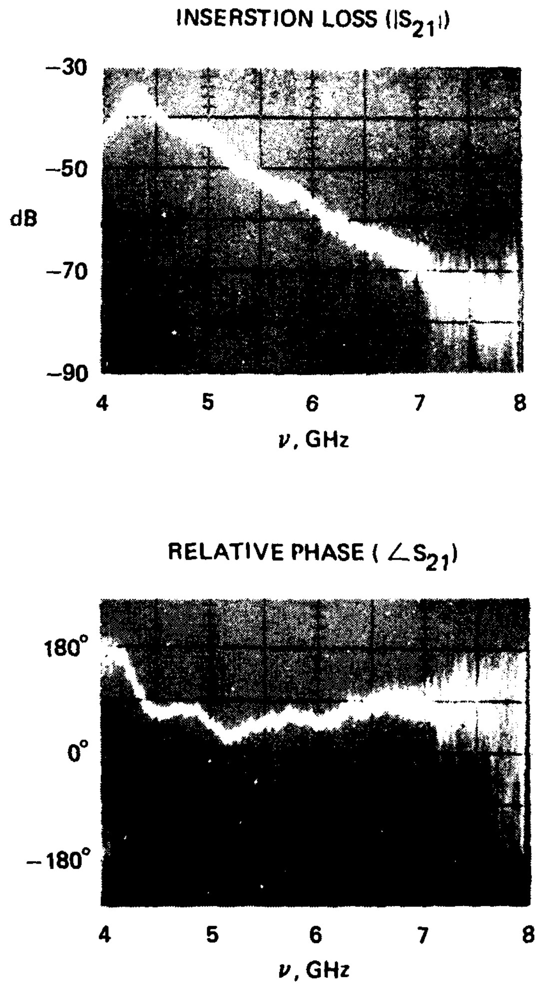

Figure 10.
The transmission characteristics of a microwave link composed of a Hitachi HLP-2400U BH laser and a Rockwell heterojunction photodiode. The laser was biased at $I = 42$ mA = $1.85\ I_{th}$.

Figure 11 shows the microwave power (at 2 GHz) as determined from the spectrum analyzer against the dc detector photocurrent. The variable ND filter was used to attenuate the laser beam. The figure basically tells us that the rf portion of the optical signal suffers the same amount of attenuation as the dc portion of the signal in our measurements. The slope of the graph is 2 because the rf power is proportional to the square of the rf current.

One way to keep the laser resonance out of the 4- to 6.5-GHz band is to bias the laser only slightly above threshold such that the resonance frequency is below 4 GHz. The advantage of such an approach is that it minimizes the danger of laser damage. The disadvantage is that the response roll-off is very large in the band of interest and some kind of compensation network is required to correct for it. Another method is to bias the laser such that the resonance frequency is pushed out to beyond 6.5 GHz. The response of the link would be relatively flat in the band of interest, but this method requires that the lasers be driven to at least 3 times above threshold. At that drive level, most of the commercially available cw lasers will suffer permanent damage. Therefore, if we insist on using direct modulation of injection lasers, we will have to bias the laser low and somehow compensate for the 12 dB/GHz roll-off (or a total variation of 30 dB over the 4- to 6.5-GHz band). If this approach is taken, the insertion loss of our link (without the fiber) will range from -40 dB to around -70 dB, and the excess noise from the laser will severely limit the dynamic range achievable.

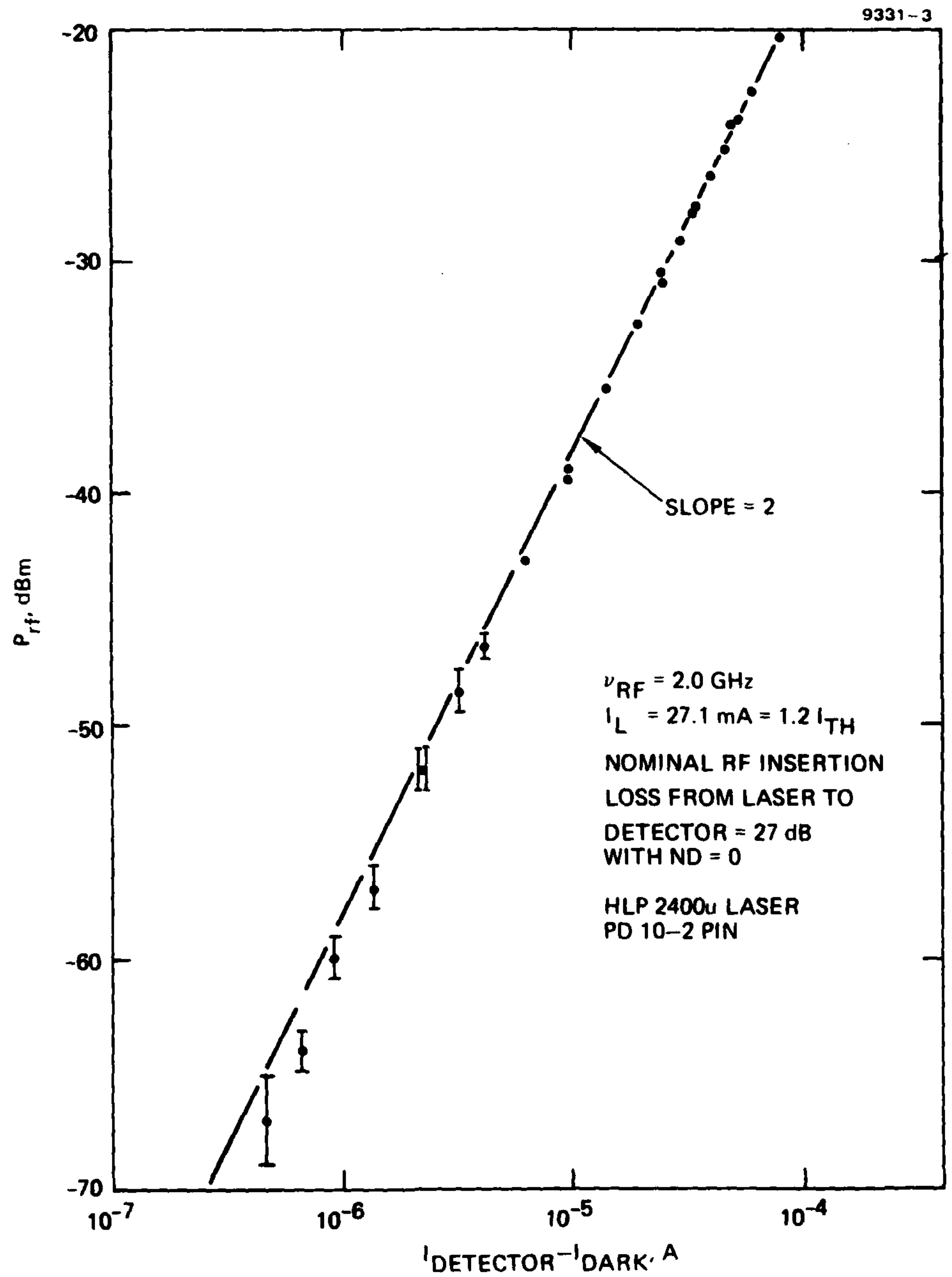

Figure 11. Demodulated rf power versus detector dc photocurrent.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

The fiber-optic delay lines studied in this contract employ the direct modulation of injection lasers to impress the microwave signal on the optical carrier. For the delay line to function properly from 4.0 to 6.5 GHz, most of the semiconductor lasers will have to be driven to at least 2 to 3 times above threshold to move the resonance peak out of the band of interest and therefore ensure uniform phase and amplitude response. However, such a high laser drive level is not compatible with cw long-life operation of the device. And, in addition, such a large bias would generate excess dc optical power that would either saturate the photodetector or set a background shot noise limit on the dynamic range of the system. Furthermore, rf impedance of the injection laser is poorly matched to the conventional 50-Ω source impedance. This will cause substantial reflection loss for the incoming microwave signal.

The laser frequency response has been studied and found to be rather nonuniform. The simple theory predicts that the amplitude response of the laser is flat in frequency all the way from dc until the resonance frequency is reached. In reality, there is always a decrease in amplitude response just before the resonance peak appears. This "dip" becomes more significant as the resonance frequency goes up. Thus, it appears that simple current modulation of injection lasers cannot produce a smooth flat frequency response unless external equalization circuits are used.

There are a few photodetectors available that would meet the requirements of the program, such as the Rockwell GaAs-GaAlAs photodiode, the Spectra Physics high-speed detector, and GaAs microwave FETs. In general, though, the saturation level of these detectors will be low due to their small size. Hopefully in the future, by using external modulation, the problem of large dc optical background level can be substantially reduced.

On the modulation aspect, it seems that injection laser direct modulation can readily be used up to about 4 GHz with reasonable bias current. Beyond 4 GHz, the laser modulation efficiency goes down drastically, probably due to carrier diffusion in the lateral directions. Also, since the resonance frequency is proportional to the square root of the driving level, the lasers must be driven beyond their capacity in order to extend the frequency of operation. It is clear from this study that to achieve a wide-band fiber-optic link will definitely require the external modulator approach. Although the complexity of the system and the microwave power requirement will increase, this approach can potentially give rise to a system with bandwidth in excess of 10 GHz. It has been shown that efficient traveling-wave phase modulation in $LiNbO_3$ channel waveguides can be achieved with bandwidths of more than 10 GHz. A simple calculation reveals that such a modulator is capable of linear response with better than 30-dB dynamic range at $\pi/2$ bias point with 1 dB compression.